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ABSTRACT

One approach to the study of cognitive processes highlights the distinctions between expert and novice problem solvers. This approach attempts to discover how experts and novices differ in the way they organize, retain and use domain related knowledge. It appears to some that what is learned from expert-novice research can help teachers to teach problem solving more effectively to students. This paper discusses some of the results of a study involving experts and novices in the domain of elementary mechanics. Also included is a brief review of research that has characterized differences between expert and novices as well as some general implications for instruction. (CW)

Problem Solving: Learning From Experts and Novices*

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How can cognitive research results contribute to the goal of teaching students to solve problems more effectively? Solving problems is a complex and intellectually demanding human activity requiring several types of knowledge and skills. This makes effective teaching of problem solving methods both a difficult and challenging undertaking. While research cannot yet offer a comprehensive theory of problem solving to guide instructional practices, a growing body of research has enhanced our understanding of those factors that contribute to proficient problem solving.

One popular approach to the study of cognitive processes highlights the distinctions between expert and novice problem solvers. These studies attempt to discover how experts and novices differ in the way they organize, retain and use domain related knowledge. While it is imperative that we be cautious in applying results to the design of instructional materials—i.e., in not assuming that the performance of experts is optimal or that novices can accomplish without explicit procedures what experts perform automatically from years of experience—it would appear that expert-novice research can help us to teach problem solving more effectively to our students. To illustrate how, I will discuss some of the results of a study involving experts and novices, in the domain of elementary mechanics, that we are currently completing at the University of Massachusetts. In addition I will discuss some general implications for instruction. I will begin by providing a brief review of the research which has characterized differences between experts and novices.

In physics, as in other domains, experts and novices organize and retain knowledge in distinctly different ways[1-6]. Experts store information in clusters or chunks, the organization of which is largely hierarchical. Fundamental concepts occupy the highest, most accessible levels of the hierarchy, while domain-related factual information is stored at the lowest level and accessed via reference to more fundamental concepts. Hence being an expert means having: (a) more conceptual chunks in memory, (b) more relations or features defining each chunk, (c) more interrelations among chunks, and (d) effective methods for retrieving related chunks.[7]

Such organization appears to profoundly influence problem solving. Experts generally begin a problem analysis by focusing on the problem's "deep structure" (i.e., the fundamental principles, or concepts that could be applied to solve it). Then they qualitatively analyze the problem based on the concepts selected, and finally, develop a strategy for achieving a solution before executing any procedures. In contrast, novices tend to cue on a problem's "surface features" (i.e., problem jargon, descriptors of the physical set-up, etc.), and they proceed toward a solution focusing on equations that might be used to solve the problem without examining the qualitative structure of the problem.

These differences between experts and novices give rise to an important question: Is problem solving proficiency merely a function of aptitude and experience in a domain, or is it the result of the specific knowledge structures we observe in the expert? One approach to answering this question is to investigate whether good novice problem solvers show more similarity to experts in terms of their knowledge structures than do poor novice problem solvers. If so, this would give more credence to the suggestion that the experts' cognitive structures are relevant to novice problem solvers.

We attempted to address this question through investigation of problem categorization. Problem categorization has been identified as a crucial component of problem solving, since, as a problem is read, a mental representation of the problem is constructed, the formation of which implies a categorization of the problem. For experts this process suggests possible solution strategies, and may directly influence ability to generate a successful solution to a problem.

To investigate the similarities among experts, and among good and poor novice problem solvers, we designed a similarity judgement task in which the subject is given two problems to compare: a model problem and a comparison problem. The subjects were asked to decide whether the same approach would be used to solve both problems and to provide the reasoning behind their decision. By varying the surface feature and deep structure similarity of the comparison and model problems we could determine the relative importance of these factors to problem categorization. The judgement task was given to 7 expert physicists, and 45 novices who had just completed an introductory physics course at the University of Massachusetts. The major results were:

- Experts' reasoning in judging solution similarity was guided by physics principles almost exclusively. Experts were essentially flawless in identifying the appropriate principle(s) needed to solve a problem (98% success rate).

- Novices differed from experts, and from each other, in the degree to which they utilized principles in their judgments of solution similarity. They could be divided into three groups based on their pattern of reasoning: 1) mainly principles, 2) mainly surface features, and 3) a mix of principles, surface features, specific equations, and ancillary concepts. Principle users made more judgments that were correct on the basis of deep structure than did those who used either surface features or a mixture of problem attributes.

- The criteria used to categorize a problem were related to problem solving proficiency. Principle users scored the highest on a problem solving task given to all novices, while surface feature users scored the lowest.

- There was a significant positive correlation between the frequency of attempts to reason with principles and score on the problem solving task; a significant correlation remained even when the level of mathematics proficiency (which we take loosely as a measure of innate ability) was held constant. Put succinctly, novices who attempt to categorize problems using principles tend to be better problem solvers.

We think that these findings support the notion that domain specific categories play an important role in the development of proficient problem solving. In the particular case of elementary mechanics, the deep structure categories observed among experts are also observed among good novice problem solvers. Further, these expert-like categories are meaningful to the better novice problem solvers in the sense that novices consider the category labels to represent adequate justification for their judgments of solution similarity. This is in contrast to novices who feel the need to specify the equations that are necessary for solving the problem or who believe that surface feature attributes of a problem alone can provide an indication of the solution method.

A second question that arises while considering differences between experts and novices is whether we can help novices to become better problem solvers by precipitating the formation of expert-like knowledge structures and by encouraging them to use an expert-like problem solving approach. We investigated this question using a menu-driven, computer-based environment to constrain the problem solving activities of novices. This environment, called the Hierarchical Analysis Tool (HAT), combines declarative and procedural knowledge in a hierarchical structure and is based on the top-down problem solving approach observed in experts. The HAT poses questions to the user, questions that experts might pose while analyzing an elementary mechanics problem.

The first menu asks the user to select the principle which can be applied to solve the problem. The content of subsequent menus is determined solely by the prior selections of the user (independent of the particular problem), and become increasingly specific as one progresses through the hierarchical structure. When the analysis is complete the user is provided with a set of equations that are consistent with the menu selections made during the analysis. If the analysis was carried out correctly these equations could be used to generate a solution to the problem. The HAT is flexible enough to accommodate the majority of problems encountered in a typical first-semester, calculus-based mechanics course.

In our study, subjects solved 25 classical mechanics problems over five one-hour sessions using the HAT. Two control groups were used for comparison purposes: one solved the problems using the textbook as a resource, while the other solved the problems using a novice-like, computer-based environment called the Equation Sorting Tool (EST). The EST contained 178 equations taken from an introductory textbook. This equation data-base could be searched and sorted via surface feature terminology (e.g., by problem types such as "inclined plane problems," by variable names such as "velocity," or by physics terms such as "potential energy.").

The effectiveness of the HAT was compared against that of the two control treatments in three areas: 1) Problem categorization, 2) Explanations of physical situation and 3) Problem solving ability. Tasks were administered in each area both before and after treatment; hence, we were able to observe shifts in performance that resulted from the treatment. The major results were:

- Only the group using the HAT showed an improvement in categorizing problems according to principles. We believe that use of the HAT promoted this shift because it highlights the importance of applying principles as the first step in the analysis of a problem.

- Only the HAT group improved in their qualitative explanations of physical situations. The results suggest that in forming principle-based problem categories, novices begin to organize their knowledge around these categories, giving priorities to major concepts and principles.

- Pre- and post-tests of problem solving provided mixed results. Use of the HAT did lead to significant improvement in problem solving, but not beyond that achieved by using the textbook.

- The rate at which novices made errors on questions that experts can routinely answer suggests that novices who have finished one semester of physics are not yet able, as a group, to work within an expert-like approach without some type of feedback. Despite this fact, simple exposure to the expert-like approach resulted in a shift toward expert-like behavior.

The results of the studies described above allow us to draw two general conclusions. First the ability to categorize problems according to deep structure is a critical element of expertise. This is reflected in the fact that good problem solvers are more like experts than are poor problem solvers in their use of principles in categorizing mechanics problems. Second, teaching students to use principles effectively is not a simple matter, even within a framework specifically designed to direct reasoning from principles. While the aim of instruction is to produce proficient and flexible problem solvers, most instruction in science unintentionally accomplishes the opposite: rigid, surface feature bound problem solvers. Why and what can we do about it?

Traditionally, science courses have been taught in a cyclical fashion: 1) present new material, 2) show how this material can be applied to solve problems through worked out examples, and 3) have the student apply this material in homework problems. The hope of the instructor is that the students will extract generalizable procedures for attacking a wide class of problems. What actually tends to happen is that students focus on the results of the procedure (i.e. the formulas) and rarely perceive the procedure. Consequently students develop schemes for storing equations that enable them to "find" the correct one when needed. The formulas are only loosely tied to any conceptual framework, and act relatively independently.

Note that the expert instructor has reasons for choosing the path taken in demonstrating a solution method, but those reasons are often left tacit and unexplained. For the student to grasp the use and implementation of a principle the experts' procedural methods must be made explicit.

Three factors seem critical in teaching students to solve problems in a complex domain, such as classical mechanics. First, students must be assisted in building an overall conception of the structure of the domain, which includes organizing knowledge, and making explicit the procedures that good problem solvers use to solve problems. For classical mechanics problems, a few hierarchical procedures are sufficient for solving a majority of the problems that are encountered. Second, procedures should be taught in a way that makes them meaningful to the student. This means that procedures must be taught in the context of problem situations, and extended to different kinds of situations, while highlighting the commonalities among the situations. Third, explicit attempts must be made to link conceptual and procedural knowledge. Concepts and procedures are related, and students are more likely to be able to reproduce a procedure if it is meaningfully related to their conceptual knowledge.

Our experience with the hierarchically structured approach suggests that the development of students' physics knowledge and problem solving skills can be facilitated through activities which actively engage them in problem solving tasks that highlight the relationship of concepts and procedures. Tasks involving problem categorization or qualitative explanations, can serve both to provide a means to focus students' attention on the knowledge organization important for proficient problem solving, and to provide teachers with an independent measure of students understanding.

Finally, there is a need to alert students to tendencies they may have which will interfere with their understanding of a domain and their progress toward problem solving competency. It seems that stude~ts, especially those having difficulties, spend far to much time on faulty paths, reinforcing habits that are detrimental to becoming good problem solvers. This practice is often excused with statements to the effect that "struggling" with problems is a part of the learning process. It is time to change this view. We enthusiastically provide students with the conceptual basis of a domain, yet we adopt a hands-off policy when it comes to the complex knowledge required to effectively apply these concepts in problem situations. To help our students effectively use their conceptual knowledge we must begin to give more attention to the organization of this knowledge and its relationship to the procedural knowledge so critical to problem solving.

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